

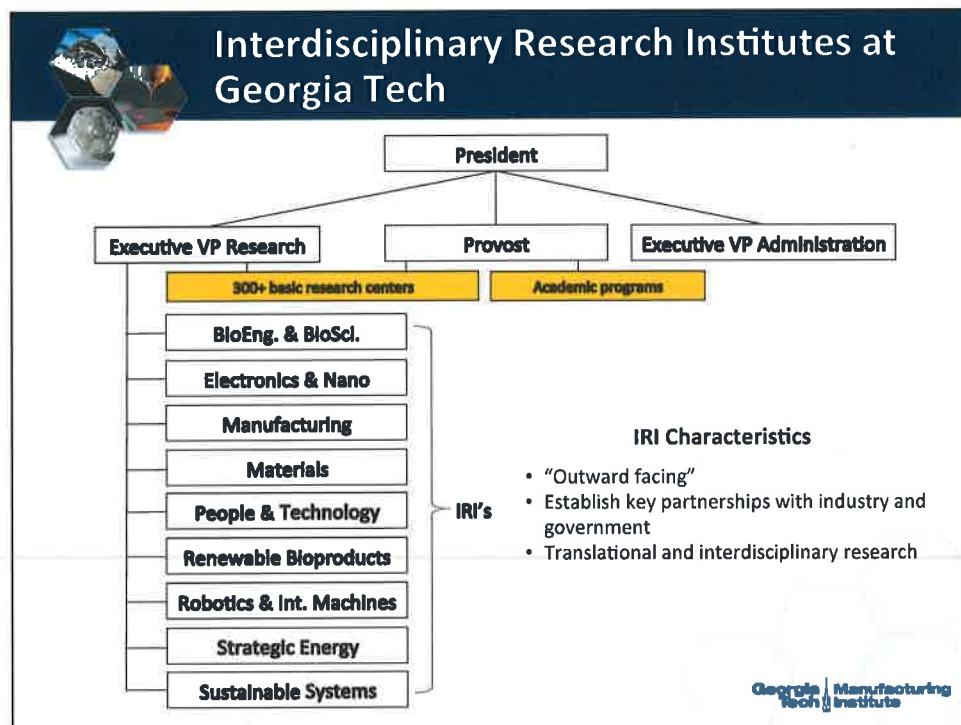


Printed Electronics Research at Georgia Tech Manufacturing Institute

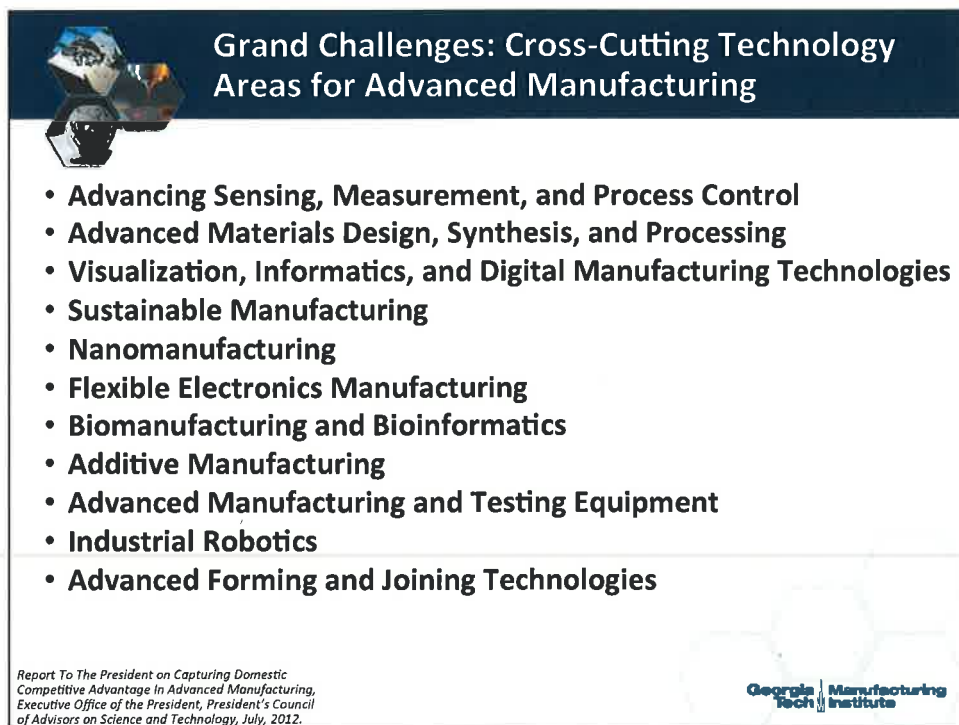
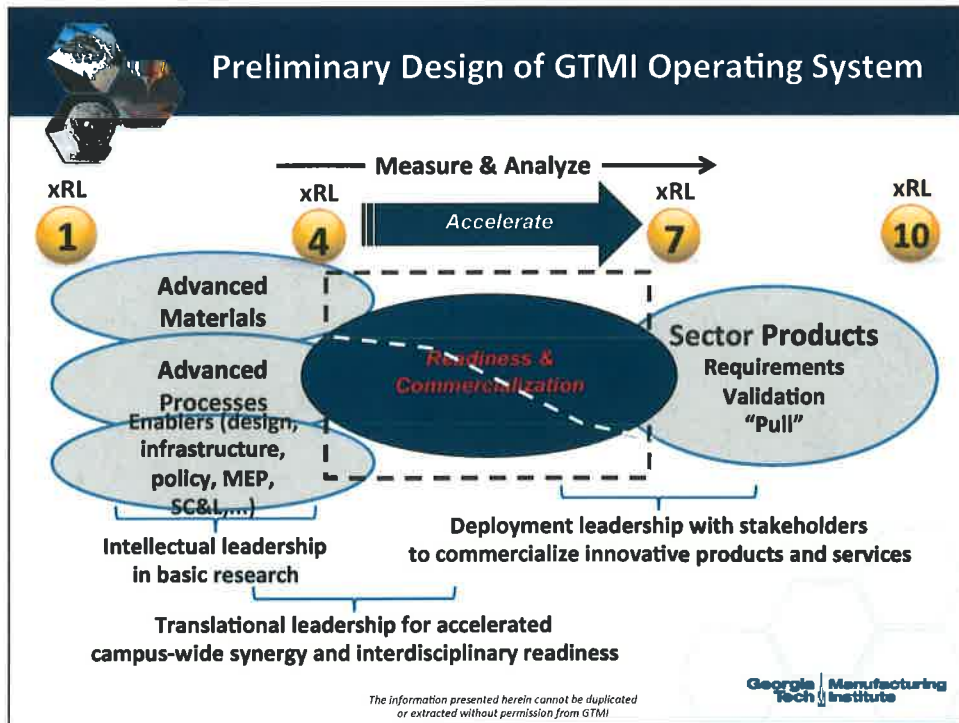
Chuck Zhang
 School of Industrial & Systems Engineering
 and Georgia Tech Manufacturing Institute

March 18, 2015











Grand Challenges: Cross-Cutting Technology Areas for Advanced Manufacturing – Related to Printed/Flexible Electronics

- Advancing Sensing, Measurement, and Process Control
- Advanced Materials Design, Synthesis, and Processing
- Visualization, Informatics, and Digital Manufacturing Technologies
- Sustainable Manufacturing
- Nanomanufacturing
- **Flexible Electronics Manufacturing**
- Biomanufacturing and Bioinformatics
- Additive Manufacturing
- Advanced Manufacturing and Testing Equipment
- Industrial Robotics
- Advanced Forming and Joining Technologies

Over half of the challenges are related to Printed/Flexible Electronics!

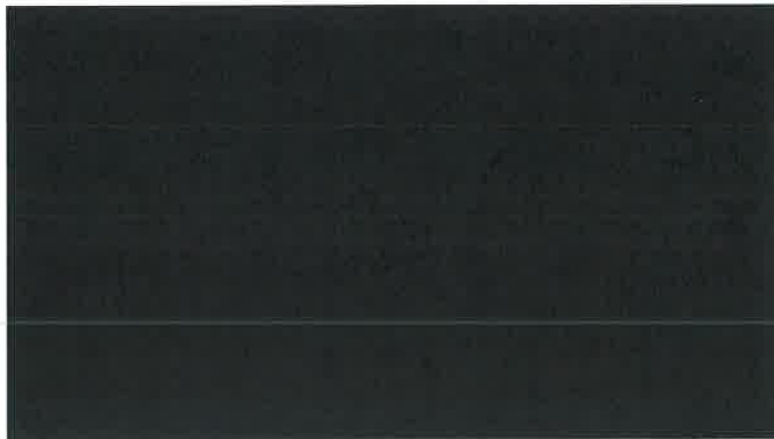
Report To The President on Capturing Domestic Competitive Advantage In Advanced Manufacturing, Executive Office of the President, President's Council of Advisors on Science and Technology, July, 2012.

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Printed and Flexible Electronics: An Enabling Technology for Revolutionary Products

Nokia Concept Phone: *Morph*



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Transformative Printed Electronics Research at GTMI

- Printed Electronics for Smart Materials with Advanced Sensing
- Integration of 3D Printing and Printed Electronics
- Printed Electronics for Medical Applications
- ICME-based PE Process Modeling, Monitoring and Control for High Quality and Repeatable Manufacturing
- Scalable Manufacturing for Printed Electronics

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GTMI's Printed Electronics Capabilities Highlights

- Optomec Aerosol Jet® Printing (AJP) system with high resolution printing (~10µm printed line width and nanometers thickness)
- Characterization tools for materials and printed devices
- Printed electronics prototypes fabricated at GTMI with the AJP system: strain, temperature and gas sensors, pressure sensors and actuators, organic transistors, RFID tag, high frequency antenna, and energy storage devices



Optomec AJP 300
PE System at GTMI

Thermal conductivity
measurement



Electrical conductivity
measurement




Surface profiler



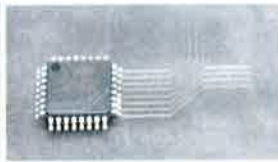
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Prototypes/Samples Printed at GTMI




Strain sensor array printed with silver ink




Interconnects linked with IC chip pins




RFID tag on silicone



Temperature sensor printed with carbon nanotubes



RFID tag and antenna array on carbon fiber prepreg





High frequency antenna

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We Have Worked with a Wide Range of Ink and Substrate Materials


Inks


Metal NP



CNT


Graphite



CNT-Silver NP



Polyimide

Substrates


Polyimide (Flexible Films)


Carbon Fiber Prepreg (Composites)


3D Flexible Surface


Coated Surface


3D Printed Part


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Application Case: Direct Printing of Sensors on Laminate for Composite Manufacturing Process and Finish Component Structural Health Monitoring

Objectives

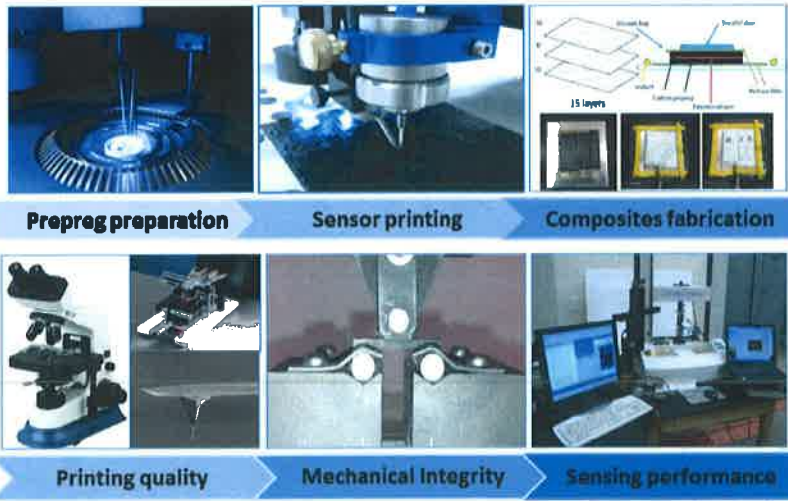
- Print strain and temperature sensors directly on preregs and embed them into composite laminates
- Investigate the effects of sensors embedment on composite mechanical properties
- Monitoring of manufacturing process and structural health of composites with printed sensors



▪ Preregs: unidirectional carbon fiber/epoxy

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Experimental Procedure

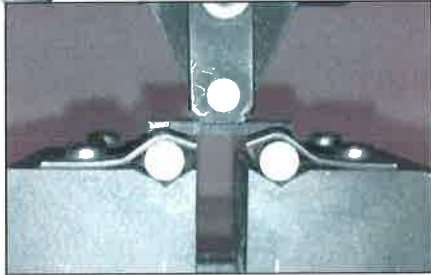


Prepreg preparation Sensor printing Composites fabrication

Printing quality Mechanical Integrity Sensing performance

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Inter-laminar Shear Strength of Various Composite Panels




Takeaway

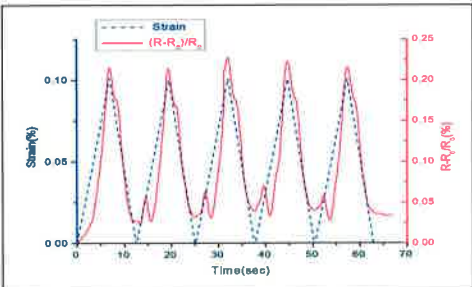
10% pre-cure retained full mechanical performance

Composite Sample Type	ILSS (MPa)
1. Raw (0% cured) prepreg with printed sensor	40.63±1.52
2. Pre-cured (10%) prepreg with printed sensor	40.88±1.27
3. Fully-cured prepreg with printed sensor	22.41±1.13
4. CFRP without sensor	41.13±0.78

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Printed Electronics-Based Strain Sensor Performance





Cyclic tests of strain and resistance change as a function of time for printed strain sensor embedded in composites

Type of Strain Gauge	Gauge Factor
Printed Gauge	2.2 ± 0.06
Commercial Metal Gauge	~ 2



Strain sensing test apparatus

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Design Validation of Composite Space Structures with Embedded Strain Sensors

- Carbon fiber composite hinge for deployable radiator
- Three AJP strain sensors embedded in the hinge for design optimization and FEA model validation
- Testing under various mechanical and temperature loadings






In collaboration with Genesis Engineering Solutions, Inc.

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Integrated Composite Design, Manufacturing Process Monitoring and Service with Printed Electronics



Design Model Validation


Manufacturing Process Monitoring

Finished Product Structural Health Monitoring


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A Case for Medical Applications of Additive Manufacturing Technology: Heart Valve Phantom




- **Models for patient education**
- **Physical objects for medical imaging and computational models validation**
- **Models for pre-surgery planning and practice**




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Medical Applications of Multi-Material 3D Printing Technology




CT Scan







CAD/STL Models





Printed Valve




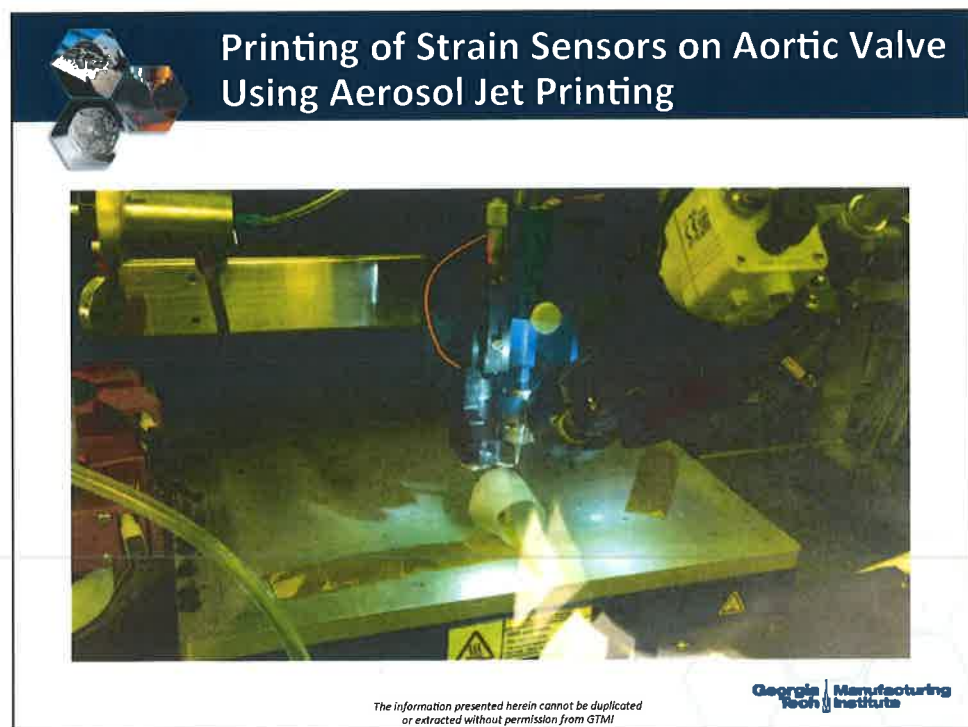
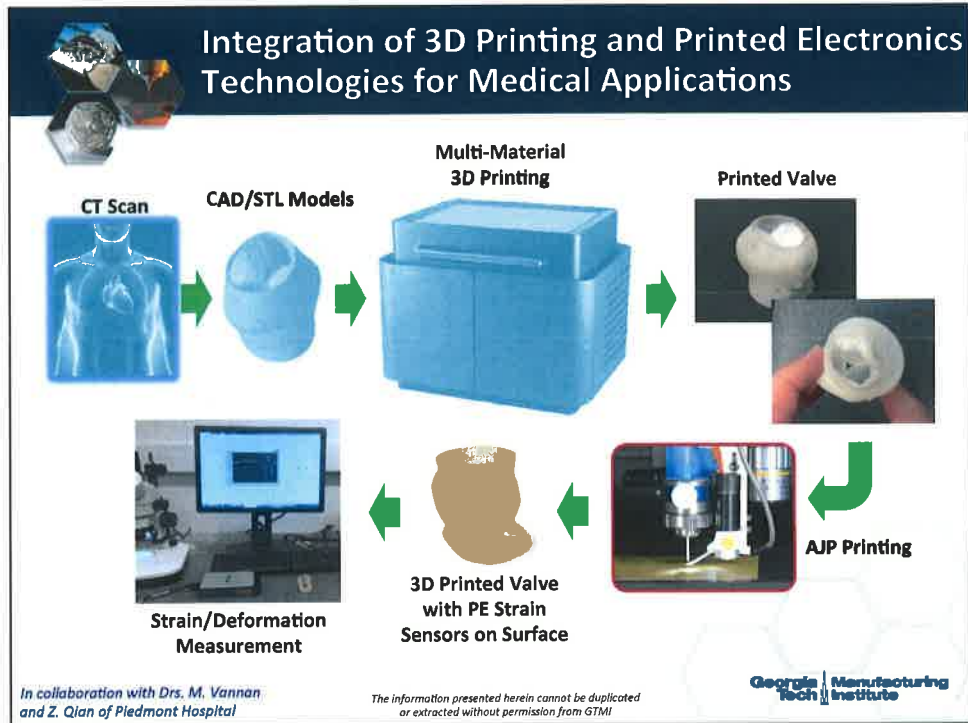




- **Mimic human heart valve structure and conditions for pre-surgery planning, patient education and medical device (e.g. stent) evaluation**
- **Multi-material 3D printing allows fabrication of valve prototypes with matching mechanical behavior and conditions (such as calcium deposition)**

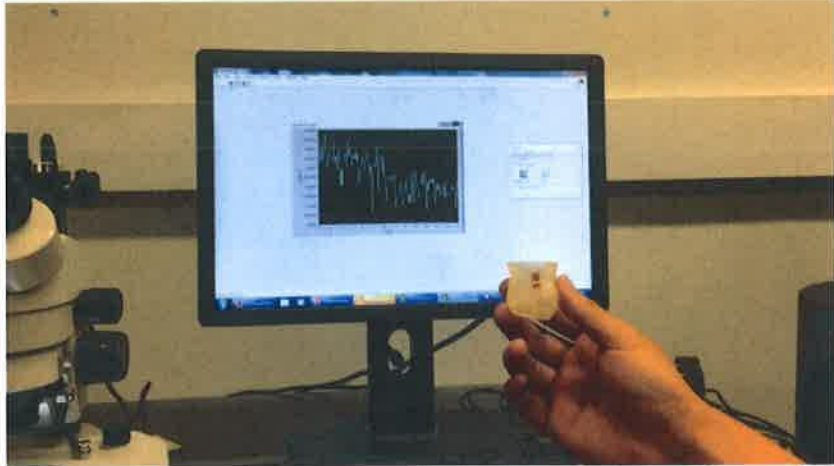
In collaboration with Drs. M. Vannan and Z. Qian of Piedmont Hospital

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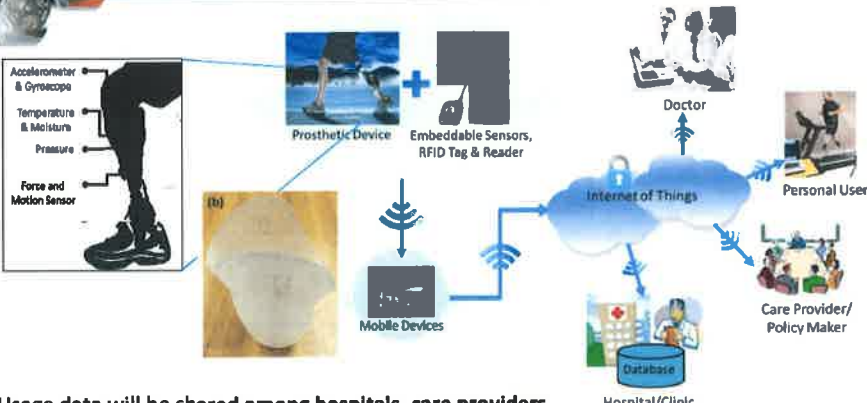
Demonstration of Strain Sensing for Aortic Valve



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Next Generation of Personalized Prosthetic Products and Services

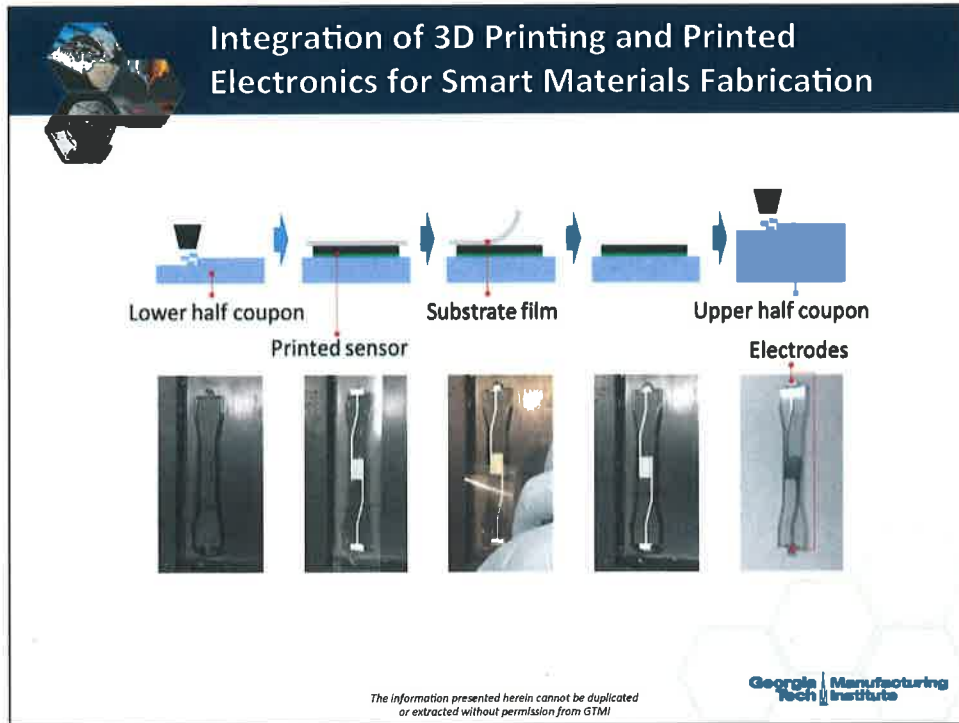


- Usage data will be shared among hospitals, care providers and practitioners for effective healthcare for veterans
- Insurance claim criteria developed from usage data analysis will be used as quantitative standards
- Manufacturing and materials database will be shared with socket manufacturers

In collaboration with GT-AP and Georgia State University

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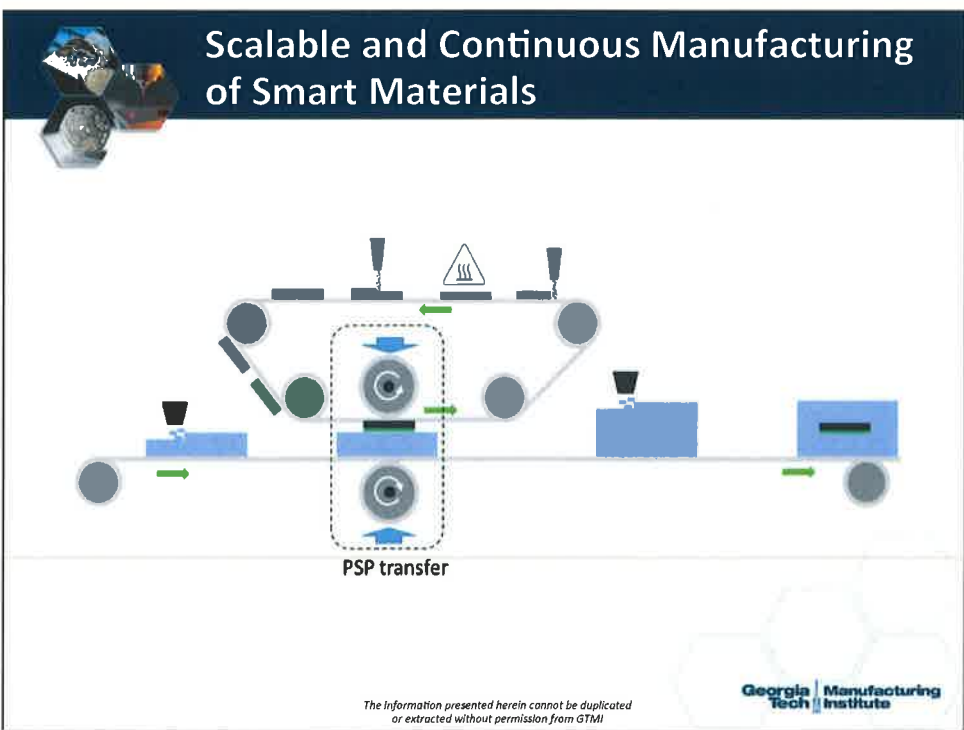
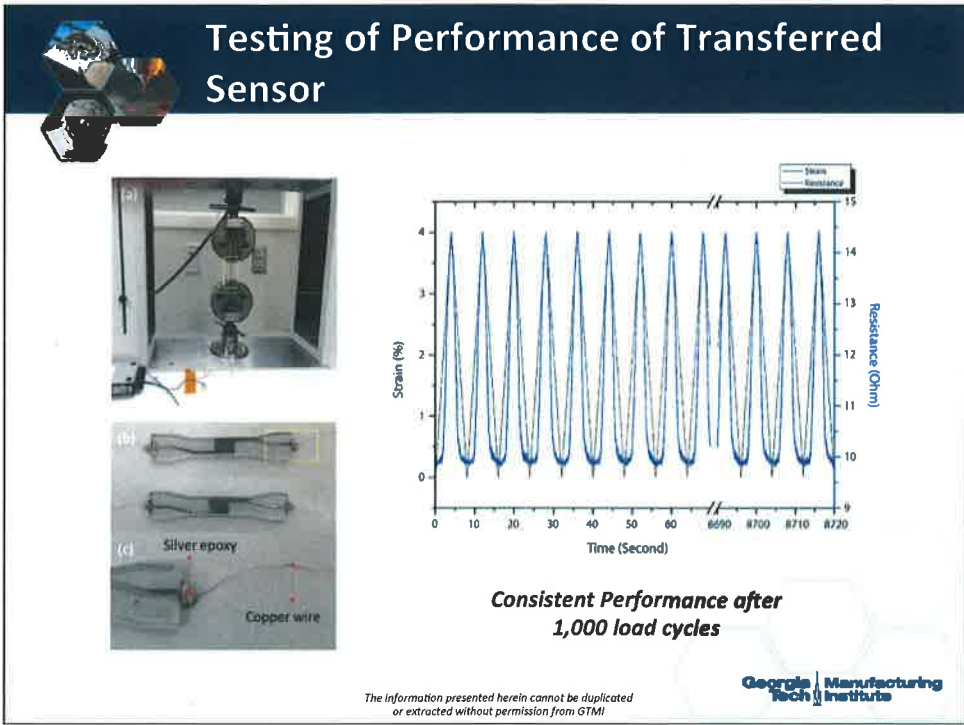


Measurement of Printed Sensors Conductivity Before and After Transfer

Sample Number	Substrate of Printed Pattern	Adhesive Layer	Thickness of Printed Pattern (μm)	Resistance between Electrodes (Ohm)	
				Before Transfer	After Transfer
1	PTFE	No	2.15 ± 0.07	8.8	9.7
2	PTFE	No	1.89 ± 0.11	10.3	10.9
3	PTFE	Yes	2.81 ± 0.13	12.8	13.0
4	PFA	No	2.06 ± 0.09	9.6	10.2
5	PFA	Yes	2.63 ± 0.11	13.4	13.5

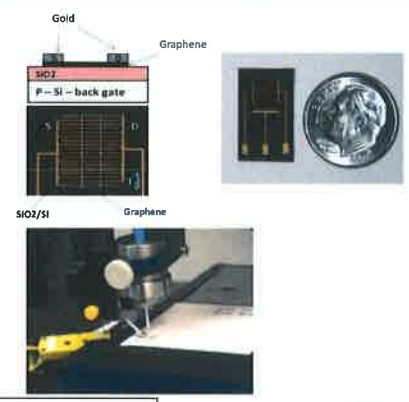



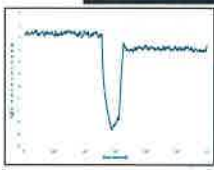
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Collaborative Project: Fabrication of CNT-based High Sensitivity Gas Sensors for Homeland Security Applications

- Long-term monitoring of chemical vapors
- Standoff detection
- Low vapor pressure of explosives requires high sensitivity
 - 10 ppb for TNT, 10 ppt for explosives (RDX, PETN)
- Deployed on buildings, vehicles, clothing, tickets
 - Low cost, small size
- AJP printed sensors outperform those by other manufacturing processes (5X sensitivity)

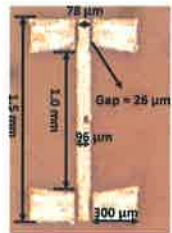






In collaboration with Dr. Judy Song, Electro-Optical Systems Lab, Georgia Tech Research Institute

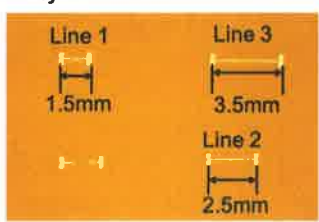
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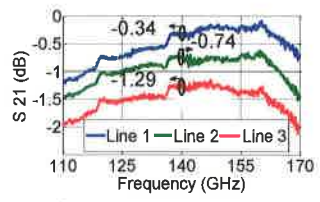
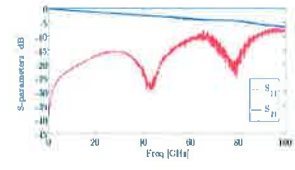
Collaborative Project: Printing of High Frequency Transmission Lines and Conformal Antenna




CBCPW Microstrip



AJP of D-Band Transmission Lines

Loss: AJP < 0.5dB/mm v.s. Ink-jet > 2.5dB/mm



Printed Conformal Antenna

In collaboration with Dr. John Papapolymero of GT-ECE

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Collaborative Project: 3D Packaging by Vias Filling

125 μ m vias filled with silver Ink

In collaboration with Dr. John Papapolymero of GT-ECE

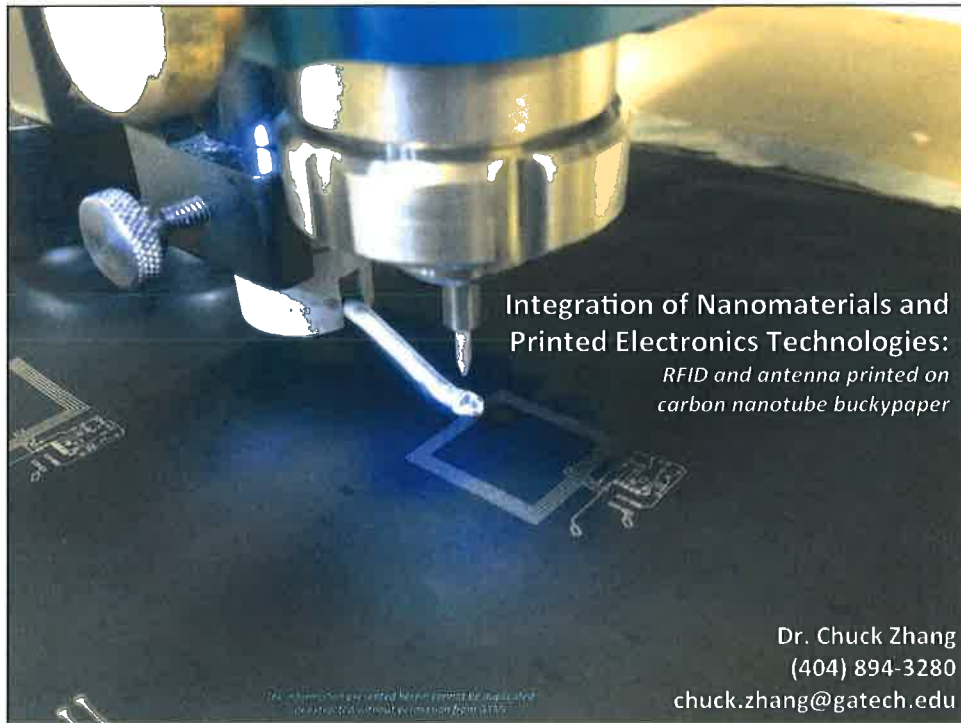
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 - Dr. John Papapolymero, GT-ECE
 - Dr. Judy Song, GTRI
 - Dr. Ben Wang, GT-ISyE and GTMI
 - Dr. Kevin Wang, GTMI
- **Graduate Assistants:**
 - Scott Chang GT-ISyE and GTMI
 - Charles Wu, GT-MS&E and GTMI

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Questions & Comments

Thanks!

Chuck Zhang

Tel: (404) 894-3280

Email: chuck.zhang@gatech.edu

